DEMO design and Diagnostics: a short summary of studies in EU

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1. Short Introduction on present status of tokamak plasma scenarios

2. DEMO design principles (tokamak fusion energy demonstrator):
   - MODELS for DEMO steady state and pulsed devices,
   - physics analysis
   - pros and cons

3. DEMO diagnostics and controls:
   - principles of fusion reactor control and sensors (diagnostics)
   - Minimum set of diagnostics for DEMO (pulsed and steady state)
   - Necessary diagnostics for machine protection and burn control
   - R&D needed

4. Conclusions

Aims:
Where we are in the plasma scenarios

EU FUSION ENERGY ROAD MAP

Key points on the design
Of DEMO, motivations for a Pulsed DEMO

The diagnostics are sensors
For DEMO controls
NO PHYSICS STUDIES ON DEMO
Few systems only for BURN CONTROL and Machine protection
KEY POINT: The resistance to neutron fluence
(total neutron flux integrated in time)
JET and ITER discharge as seen by a IR camera
In a plasma contained in a toroidal device with axial magnetic field, a current is induced by a transformer.

A magnetic field results with elical field lines which close after a certain number of turns on surfaces called ‘rationale surfaces’

\[
B_{\text{pol}} \approx \frac{B_{\text{toroidal}}}{10};
\]

Safety factor \( q = \frac{\text{number of toroidal turns}}{\text{n poloidal turns}} \)

\[
q = \frac{5a^2B}{RI} \left(1 + \frac{k^2}{2}\right)
\]

Magnetic shear \( S = \frac{q}{r} \left(\frac{dq}{dr}\right) \)
Regimes of plasma confinement are classified in relation to the spatial scales relevant:

i) Regimes where the relevant spatial scale is the plasma dimension are named L-mode (low confinement modes).

ii) Regimes where the Larmor radius is the fundamental relevant scale are named H-modes (High Confinement).

The transition to H-mode is linked to a threshold power $P_{L-H} \sim C B_T n^{0.75} R^2$.

For example in JET $P_{L-H} \sim 8$ MW.
Kadomtsev (1975) e Connor e Taylor (1977) demonstrated

$$\omega_c \tau_E \propto B \tau_E \propto f (\rho^*, \beta, \nu^*, q, \ldots)$$

fit of data of confinement multi machine database

$$\omega_{ce} \tau_E \propto \rho^{-2.7} \beta^{-0.9} \nu^{-0.01} \ (scaling \ IPB98(y,2))$$

Recent Experiments on JET (EU) e DIIID (Ga, USA) demonstrated that in the range of parameters useful for a demonstrative reactor

$$\omega_{ce} \tau_E \propto \rho^{-3.0 \pm 0.3} \beta^{0.0} \nu^{-0.3}$$

( D McDonalds and J Cordey Conf IAEA 2004,
McDonalds IAEA 2006, Valovic Nuclear Fusion 2006)
Operational regimes in a tokamak: correspondence of current profiles $\leftrightarrow$ pressure profiles

$\frac{q}{B/I}$ pressure $= nT$

E Joffrin and X Garbet Conf IAEA 2004,
T Luce IAEA FEC Conference 2006
Example of a discharge in ELMy H-mode

ELMs (edge localized modes) correspond to instabilities generated when locally the beta limit is reached.

Internal Energy of the discharge

- Max. $I_p=4\text{MA}$, $\beta_N=1.5$, Type I ELMy H-Mode
- One of the highest D-D yields achieved on JET (Dec2003)
- $\rho^*/\rho^*_{\text{ITER}} = 1.7$

J Cordey et al. Conf. IAEA 2004
Improved LHCD coupling leads to strong magnetic shear reversal during preheat

- strong internal transport barriers

- virtually no power threshold when compared to Optimised Shear

Advanced Scenarios: current profiles and formation of internal transport barriers
Internal Transport Barriers in Advanced Tokamak discharges

Profiles of density and ion temperature in JET record discharge in the FIRST Deuterium Tritium campaigns.
Power from fusion in magnetic confinement.

\[ P_{\text{fusion}} = \frac{1}{4} n_{\text{ion}}^2 \langle \sigma \nu \rangle E_{\text{fusion}} \sim (nT)^2 \]

\[ P_{\text{fusion}} = 1.08 \beta^2 B^4. \text{ MW/m}^3. \]

\[ \beta = 2 \text{ nT} / (B^2/2\mu_0) = \frac{\text{kinetic total pressure(ions+electrons)}}{\text{magnetic pressure}} \]

For example. \( (B^2/2\mu_0) = 10000 \text{ pascal} @ B=0.5T \)

Typical value of beta \( \beta \sim 1-10\% \)
Comments on Pfus vs (limits of) beta

\[ P_{\text{fusion}} = 1.08 \beta^2 B^4 \text{ MW/m}^3. \]

\[ \text{D+T} \rightarrow \alpha(3.5 \text{MeV}) + n(14.1 \text{MeV}) \]

\[ Q_{\text{fusion gain}} = \frac{\text{fusion power}}{\text{heating power}} \]

at the steady state \( \Rightarrow P_{\text{heat}} + P_{\text{alpha}} = \frac{3 n T_e}{\tau_E} \)

\[ \tau_E = \text{energy confinement time} \]

\[ Q = \frac{P_{\text{fus}}}{3 n T_e - P_{\text{fus}}} = \frac{\overline{Q}}{1 - (\overline{Q} / 5)} \]

\[ \overline{Q} = \frac{P_{\text{fus}}}{P_{\text{loss}}} = \frac{4 \beta^2 B^4 \tau_E}{3} \]

\( \beta \) limited by MHD stability

\( \tau_E \) limited by the turbulent transport
Gain Q versus geometry and plasma parameters

\[ \tau_E(s) = 0.0562 \times I^{0.93} \times B^{0.15} \times \left( \frac{a}{R} \right)^{0.58} \times R^{1.97} \times n^{0.41} \times P^{-0.69} \times M^{0.19} \times k_a^{0.78} \]

\[ \beta = \beta_N \frac{I}{aB}; \quad \beta_N \leq 0.035 \]

**Beta limit**

\[ \bar{Q} = \frac{4}{3} \beta B^2 \tau_E = \frac{4}{3} \times 0.0562 \times \beta_N \times I^{1.93} \times B^{1.15} \times \left( \frac{R}{a} \right)^{1.39} \times a^{-0.97} \times n^{0.41} \times P^{-0.69} \times M^{0.19} \times k_a^{0.78} \]

**Density limit**

\[ nGR = \frac{I}{\pi a^2} \]

\[ \bar{Q} \leq 0.04686 \times \beta_N \times I^{2.34} \times B^{1.15} \times \left[ \frac{R}{a} \right]^{1.39} \times a^{-1.03} \times P_{\text{loss}}^{-0.69} \times M^{0.19} \times k_a^{0.78} \]

The gain factor depends upon:

- **Geometry** (a (minor radius) and aspect ratio R/a)
- **Plasma current I**
- **magnetic field B**
- **beta \( \beta_N \)**

At a fixed geometry (R/a), magnetic field B and heating power P an increase of \( \beta_N \) and I of 10% \( \rightarrow 33\% \). increase of \( Q \)
DEMO DESIGN:
STEADY STATE AND PULSED MODELS
EU Roadmap in a nutshell

1. Plasma operation

2. Heat exhaust

3. Materials

4. Tritium breeding

5. Safety

6. DEMO

7. Low cost

8. Stellarator

- Baseline strategy
- Advanced configuration and materials
- European Medium Size Tokamaks + linear plasma + Divertor Tokamak Test Facility + International Collaborators Tokamaks
- Stellarator optimization
- Burning Plasma Stellarator

- Low capital cost and long term technologies

- ITER Test blanket programme
- Parallel Blanket Concepts
- CFETR (CN)
- FNSF (US)

- DEMO decision
- Fusion electricity

- Construction, Operation

- EU Roadmap in a nutshell

- 2010, 2020, 2030, 2040, 2050
Basic idea of steady state reactor

The idea of working at high $\beta_N$ allows for a device with lower current and dimensions since

$$P_{\text{fus}} \approx (\beta_N)^2 \cdot I_p^2 \cdot B_t^2 \cdot R^2.$$ 

Minimizes the heating and current drive needs, since it allows higher values of beta poloidal and self-generated plasma current (bootstrap current). In fact the fraction of bootstrap current scales as

$$f_B = \frac{I_b}{I_p} \approx \frac{1}{3} A^{-1/2} \beta_p,$$

$$\beta_p \approx \beta_N / \beta_T,$$

$$\beta_p = cq_{95} A \beta_N.$$ 

High $\beta_p$, low $A$ And high $\beta_N$

The remaining part of the current must be supplied by Current Drive systems.

The produced electric energy must be partly used for the Current Drive system: this part is a critical requirement for a SS reactor.
Analysis of SS DEMO MODELS
### EXAMPLES OF SS MODELS

<table>
<thead>
<tr>
<th></th>
<th>ARIES RS</th>
<th>PPCS C</th>
<th>SLIM CS</th>
<th>ITER SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(m)</td>
<td>5,5</td>
<td>7,5</td>
<td>5,5</td>
<td>6,2</td>
</tr>
<tr>
<td>a(m)</td>
<td>1,375</td>
<td>2,5</td>
<td>2,1</td>
<td>2</td>
</tr>
<tr>
<td>Aspect ratio R/a</td>
<td>4</td>
<td>3</td>
<td>2,6</td>
<td>3,1</td>
</tr>
<tr>
<td>B(T) on axis</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>5,3</td>
</tr>
<tr>
<td>I(MA)</td>
<td>11,3</td>
<td>20</td>
<td>16,7</td>
<td>9</td>
</tr>
<tr>
<td>βN</td>
<td>4,8</td>
<td>4</td>
<td>4,3</td>
<td>2,9</td>
</tr>
<tr>
<td>fB</td>
<td>0,88</td>
<td>0,63</td>
<td>0,75</td>
<td>0,46</td>
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<tr>
<td>n/nG</td>
<td>1</td>
<td>1,5</td>
<td>1</td>
<td>0,78</td>
</tr>
<tr>
<td>HH(IPBy2)</td>
<td>1,15</td>
<td>1,3</td>
<td>1,3</td>
<td>1,6</td>
</tr>
<tr>
<td>Q</td>
<td>27</td>
<td>30</td>
<td>29,5</td>
<td>5</td>
</tr>
<tr>
<td>k elongation</td>
<td>1,9</td>
<td>1,9</td>
<td>2</td>
<td>1,8</td>
</tr>
<tr>
<td>δ triangularity</td>
<td>0,5</td>
<td>0,47</td>
<td>0,35</td>
<td>0,4</td>
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<tr>
<td>Fusion Power(GW)</td>
<td>2,17</td>
<td>3,41</td>
<td>2,95</td>
<td>0,36</td>
</tr>
<tr>
<td>Heating Power(MW)</td>
<td>80</td>
<td>112</td>
<td>100</td>
<td>70</td>
</tr>
</tbody>
</table>
for realistic Current Drive values ($\gamma_{CD} \approx 0.3-0.4 \times 10^{20} \, \text{A W}^{-1} \, 10^{20} \, \text{m}^{-2}$) high bootstrap fraction is required $f_B \geq 0.7-0.8$ compatible with the power available of $110\text{MW}$.

In the PPCS papers a more optimistic $\gamma_{CD} \approx 0.7 \times 10^{20} \, \text{A W}^{-1} \, 10^{20} \, \text{m}^{-2}$, is assumed $\gamma_{CD} (\text{A W}^{-1} \, 10^{20} \, \text{m}^{-2})$
ITER steady state scenario assumes parameters ($HHIPy2=1.61, \beta_N=2.93, f_B=0.46, n/n_G=0.78$) never demonstrated in integrated way in present devices. Clearly for SLIM CS the same notation can be applied even more.
Achieved performances on DIII-D and JT-60U in transient conditions

Integrated performances achieved in transient conditions. Comparison of design values of SlimCS (red contour) and a) DIII-D discharge (#122004) and b) JT-60U discharge (#48246)
The DIII-D discharge shows an impressive set of parameters: $\beta_N \approx 4$, $HHy2 \approx 1.6$, $fB = 0.75$, at a $q_{\text{min}} \approx 2$ and $q_{95} = 5$, produced in a reversed shear $q$-profile, in presence of Internal Transport Barrier (ITB). Multiple feedback controls are needed to reach these achievements including resistive wall mode control using internal and external sets of magnetic coils, beta control using neutral beam injection and electron density control using gas-puffing. This discharge was run at low density and low radiation fraction.

The JT-60U discharge shown in fig. exhibits values $HHy2 = 1.7$, $fB = 0.92$, $ne/nG = 0.87$, $b_N \approx 2.7$ realized in a reversed shear $q$-profile with formation of ITB. Although this discharge has achieved $HHy2$, $fB$ and $ne/nG$ reactor relevant the remaining issues are $\beta_N$, fuel purity, and radiation fraction.
Pulsed DEMO design criteria
By specifying the aspect ratio, magnetic field, fusion power, temperature, density and fraction of Greenwald density, the size of the device and its plasma current is determined (the plasma current determined from n and Greenwald fraction, not from confinement requirements).

The H-factor is derived from power balance considerations rather than providing it as an input. In that way, a self-consistent solution to the simplified problem can be found.
Pulsed DEMO: model parameter design

A pulsed reactor O3GW
A=3.5 for 2.5GW R=9.5m
A=4 for 1.6GW R=9m
Npeak=1 × 10^{20} m^{-3}

The pressure profile is given by

\[ nT = \hat{n}\hat{T}(1 - \left(\frac{r}{a}\right)^2) \nu \]

In the figure \( \nu = 1 \)

\[ P_f = \frac{0.15}{2\nu + 1} \frac{R^3}{A^2} k \left(\frac{\hat{n}}{10^{20}}\right)^2 \hat{T}_{keV}^2 \text{ MW} \]
The plasma current is determined from the Greenwald density limit
Line average nG=Ip/(πa²)
Since the neL=0.67npeak:

\[ Ip(MA) = \frac{0.67}{0.8} \pi a^2 \frac{\hat{n}}{10^{20}} = 19.37 \]

\[ B_T = \frac{q_{95}}{5} \frac{A^2}{F_A S} Ip \]

q_{95}=3-3.5, k=1.75, δ=0.45, A=3.5 , Ip=19MA

we obtain:

\[ a B_T=6.5T \text{ corresponding to } q_{95}=3.5 \]
Relation Padd and H

\[
\left( \frac{Wth}{H_{IPBy2} f} \right)^{3.23} 10^{-6} + (-P_{fus} / 5 + (P_B + P_{syn} + P_{line-core}))/10^6 = P_{AddHeat} (MW)
\]

\[
P_{alpha} - (P_B + P_{sync} + P_{line}) = \frac{2470}{5} - 363 = 131;
\]

\[
P_{AddHeat} \approx 5.2^{3.23} * H_{IPBy2}^{-3.23} - 131
\]

For the plasma parameters considered
( T0=20keV, n0=1 10^{20} m^{-3}, BT=6.5T, Ip=19MA,
fraction of Argon fAr=nAr/ni=0.1% ,
and beryllium fraction fBe=1% ),
the evaluation of the power loss appearing is:
P_B \approx 165MW, P_{sync} \approx 6MW,
P_{line-core} \approx P_{Be} + P_{Ar} = 2.4MW + 190MW; Wth=383MJ; f=220;
HIPBy2=1
P_{AddHeat} = 74MW

Ploss Total = 363MW
P_{alpha} = 494MW
### D3GW vs DEMO1 and PPCS A models

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>R(m)</td>
<td>9.5</td>
<td>9</td>
<td>9.55</td>
</tr>
<tr>
<td>a(m)</td>
<td>2.7</td>
<td>2.25</td>
<td>3.18</td>
</tr>
<tr>
<td>A</td>
<td>3.5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>6.5</td>
<td>7.1</td>
<td>7</td>
</tr>
<tr>
<td>Ip</td>
<td>19</td>
<td>16</td>
<td>30.5</td>
</tr>
<tr>
<td>n20 (fG/Greenwald)</td>
<td>1(0.8)</td>
<td>1.2(1.)</td>
<td>2.3(1.)</td>
</tr>
<tr>
<td>PH(MW)</td>
<td>74</td>
<td>50</td>
<td>246</td>
</tr>
<tr>
<td>Q</td>
<td>34</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>HHIPBy2</td>
<td>1</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>Pfus (GW)</td>
<td>2.5</td>
<td>1.9</td>
<td>5</td>
</tr>
</tbody>
</table>

The parameters of the O3GW device differ substantially in the ASPECT RATIO and density with respect to DEMO1 device. The PPCS A exhibit similar geom parameters to O3GW. The pulse length of O3GW could be compatible with $t_{\text{pulse}} = 6h$ (see ref H Zohm).

Demo1 CALCULATED BY PROCESS SYSTEM CODE
\[ \tau_{\text{pulse}} = R^2 \frac{c_3 q_{95} A_r^2 \left( \frac{A_r - 1}{A_r} - \frac{b}{R} \right) - c_4 B}{c_5 B A_r^2 (1 - fCD - c_6 * 0.7 q_{95} * \beta_N * \sqrt{A_r})} \]

H Zhom  Fus Eng Des 2011
## Steady State vs Pulsed

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>PULSED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PRO</strong></td>
<td>SMALL R0</td>
<td>RELIABILITY</td>
</tr>
<tr>
<td></td>
<td>SMALL IP</td>
<td>SOLID BASIC PLASMA SCENARIO</td>
</tr>
<tr>
<td></td>
<td>LOW ASPECT RATIO</td>
<td>HIGH ASPECT RATIO</td>
</tr>
<tr>
<td><strong>CONS</strong></td>
<td>LARGE HCD</td>
<td>High COST</td>
</tr>
<tr>
<td></td>
<td>SCENARIO TO BE DEMONSTRATED</td>
<td>CYCLIC FATIGUE ON MAGNETS AND</td>
</tr>
<tr>
<td></td>
<td>EXTENSIVELY</td>
<td>SUPERCONDUCTING COILS</td>
</tr>
<tr>
<td></td>
<td>R&amp;d NEEDED TO MAKE EFFICIENT</td>
<td>PLASMA SCENARIO STILL TO BE</td>
</tr>
<tr>
<td></td>
<td>CD SYSTEMS</td>
<td>COMPLETED</td>
</tr>
<tr>
<td><strong>CONTROLS</strong></td>
<td>CONTROLS AND DIAGNOSE OF</td>
<td>TO BE CONTROLLED:</td>
</tr>
<tr>
<td></td>
<td>CURRENT and pressure profiles</td>
<td>divertor and radiation</td>
</tr>
<tr>
<td></td>
<td>MHD CONTROLS: RWM,NTMs</td>
<td>ELM and NTM</td>
</tr>
</tbody>
</table>
The advantages of pulsed DEMO are residing in the fact that we know how to run the H-mode in plasmas where the current is largely inductive. The H-mode is a well established scenario, however:

i) there are large uncertainties in the power threshold needed for the access to the H-mode;

ii) the possibility to run plasmas at a density higher than Greenwald density must be validated;

iii) the tools to mitigate the ELMs must be still fully developed;

iv) The studies of cyclic operations on the machine components inducing creep/fatigue effects on vacuum vessel blanket modules etc are still in the initial phase.

Comparison of Dimensions of PPFC DEMO models with ITER: Pulsed (A/B) and Steady State C/D
Comparison between JET/ITER and DEMO

DEMO : DEMO-NSTRATION Device

**DEMO SPECIFIC**

1. Due to TBR >1 the space available for diagnostics is likely < 5m²

2. Radiation: \( \frac{P_{\text{rad}}(P_{\text{Br}} + P_{\text{Syn}} + P_{\text{linecore}})}{(P_{\text{alpha}} + P_{\text{Heating}})} \approx 75\% \)

3. Wall material /Divertor: metal Tungsten (ITER: Be/W)

4. Neutron fluence: 30-50 X ITER Fluence

5. \( \frac{P_{\text{alpha}}}{P_{\text{heating}}} \):

<table>
<thead>
<tr>
<th>Device</th>
<th>ITER (Q=10)</th>
<th>DEMO1</th>
<th>DEMO2</th>
<th>ITER SS</th>
<th>SLIM CS</th>
<th>PPCS C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palpha/Pheating</td>
<td>2</td>
<td>7,16</td>
<td>2,42</td>
<td>1</td>
<td>5,9</td>
<td>6,1</td>
</tr>
<tr>
<td>Palpha(MW)</td>
<td>100</td>
<td>358</td>
<td>500</td>
<td>72</td>
<td>590</td>
<td>682</td>
</tr>
<tr>
<td>Pheating(MW)</td>
<td>50</td>
<td>50</td>
<td>206</td>
<td>70</td>
<td>100</td>
<td>112</td>
</tr>
<tr>
<td>Pfus(GW)</td>
<td>0,5</td>
<td>1,8</td>
<td>2,5</td>
<td>0,36</td>
<td>2,95</td>
<td>3,41</td>
</tr>
<tr>
<td>Q</td>
<td>10</td>
<td>36</td>
<td>12</td>
<td>5</td>
<td>29,5</td>
<td>30</td>
</tr>
</tbody>
</table>
DIAGNOSTICS and CONTROLS for DEMO

References:
F P Orsitto et al IAEA FEC 2014 St Petersburg paper p7-8

Conference  Diagnostics for Fusion Reactors , Varenna september 2013

MAIN MESSAGES

- DEMO diagnostics should focus on high priority parameters: *diagnostics for machine protection and basic control to be useful for BURN control in long pulses.*

- The space available for diagnostics is severely limited by the TBR (Tritium Breeding Ratio): a minimum set of systems is used to protect and control the machine.
  The engineering of diagnostics must be inserted in the overall design of DEMO from the beginning due to the optimization of the space dedicated, compatible with the TBR: likely the organization of diagnostics in PORT PLUGS of ITER will NOT be used.

- The high fluence of DEMO (30-50 x ITER fluence) put the other important constraint on the diagnostics: in practice the ITER diagnostics MUST BE REVISITED BECAUSE OF THE HIGH DPA IMPLIED IN DEMO OPERATIONS.

- Diagnostics (nearly) feasible (low extrapolation from ITER design and R&D needed):
  - *Microwave (and Far Infrared Light) techniques*
  - *Direct line-of-sight techniques (neutrons, x-rays)*
Two phases of work can be envisaged on DEMO:

I) ITER-like phase: assessment of control of Q>>10 scenario and control/training of prediction codes;

- BURN CONTROL in conditions where $P_{\text{alpha}}/P_{\text{input}} \sim 7$ is UNIQUE to DEMO
- The *training* of transport/prediction codes for Control will imply the use of diagnostics set similar to ITER

II) Power-plant phase: TBR >1.1 constraint, severely limits the access and minimum set of diagnostics must be used + codes
Environmental conditions more extreme than in ITER (>100 times higher neutron fluence):

- No electrical and refractive components close to the plasma
- Limited application for first mirrors

Very limited access possibilities

Large emphasis on
- Reliability, Maintainability, Robustness

Needs:
- Development programme for new materials
- Testing under DEMO conditions
In the ITER-LIKE phase two classes of outputs are **EQUALLY** important:

**FIRST CLASS: Plasma operation quantities to guarantee the SAFE and optimal operation**
1. Control of the burning $Q>>10$ phase (for the pulsed device including ramp-up, flat top and ramp down)
2. The divertor power loads and detachment
3. Disruption avoidance and mitigation
4. The simulation and control codes

**SECOND CLASS: subsystems monitoring and safety**
The diagnostics of the subsystems of the device include:
- i) Blanket modules
- ii) Heating systems
- iii) Wall erosion and damage monitoring
- iv) Dust measurements
- v) Creep-fatigue monitoring (*pulsed DEMO*)
## Comparison of Surface Occupation (TBR ≥1.1)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Diagnostics</th>
<th>Heating and Current Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET</td>
<td>10</td>
<td>3 + ICH antennae (internal)</td>
</tr>
<tr>
<td>ITER</td>
<td>36</td>
<td>26 (includes HNB3 and LH)</td>
</tr>
<tr>
<td>DEMO</td>
<td>3-5</td>
<td>6-10</td>
</tr>
</tbody>
</table>

**Areas (m²)**
From the neutronics calculation:
Approx the level of damage calculated for ITER lifetime (i.e. 3dpa) is found in DEMO at 0.5m from the First Wall in 5 full power years.

The First Mirror planned for ITER resistant to 3dpa can be used in DEMO at a distance of 0.5m from the Vacuum Vessel.
From the neutronics calculation:
Approx the level of damage calculated for ITER lifetime (i.e. 3dpa) is found in DEMO at 0.5m from the First Wall in 5 full power years.

The First Mirror planned for ITER resistant to 3dpa can be used in DEMO at a distance of 0.5m from the Vacuum Vessel.
Short review of FM work so far

At moment Mo and W mirror are considered as FM in ITER

Results for Polarimetry/interferometry using wavelengths $\lambda \geq 100\mu m$

Results of irradiation
To 3dpa damage on two samples of W mirrors

Fig. 5. Dependence of reflection coefficient on the sputtered layer thickness for WJ-IG and rCW mirrors irradiated to 3 dpa (points) and not irradiated (dotted curves) sides at wavelength 600 nm

V S Voitsenya 2013
In the vertical ports the neutron flux is close to be 50% LESS than the equatorial OUTBOARD ports.
Classification of diagnostics for DEMO

- machine protection
- Basic control
- ADVANCED CONTROL (ITER-like phase)

<table>
<thead>
<tr>
<th>machine protection</th>
<th>basic control</th>
<th>advanced control (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>disruption</td>
<td>equilibrium</td>
<td>alpha part measurements</td>
</tr>
<tr>
<td>heat loads</td>
<td>burn control (Te control)</td>
<td>current profile</td>
</tr>
<tr>
<td>alpha losses</td>
<td>MHD control/CD control</td>
<td>kinetic profiles (pedestal)</td>
</tr>
<tr>
<td>density control</td>
<td>ELM mitigation</td>
<td></td>
</tr>
<tr>
<td>plasma position</td>
<td>Radiation control</td>
<td></td>
</tr>
<tr>
<td>fusion power</td>
<td>kinetic measurements</td>
<td></td>
</tr>
<tr>
<td>radiation profiles</td>
<td>divertor control</td>
<td></td>
</tr>
<tr>
<td>magnetics equilibrium (MHD markers)</td>
<td>Burn control (fuel and fuel ratio control)</td>
<td>(*)Not working in power plant phase</td>
</tr>
</tbody>
</table>
Diagnostic systems FOR MACHINE PROTECTION

Minimum set of dia for Machine protection (R&D needed):

Magnetics (Hall sensors to be tested at high dpa>3, Low Temperature Co-fired Ceramic (LTCC) technology under test for ITER??)

IR Cameras (W or Mo mirrors to be tested for dpa>3)

Polarimetry (W or Mo mirrors to be tested for dpa>3)

Position reflectometry (ITER reflectometry nearly OK)

Fission chambers (ITER fission chambers to be qualified)

X-ray spectroscopy (X-ray mirrors and/or policapillary lenses to be tested)

VUV and Vis spectroscopy (*) (W or Mo mirrors to be tested)

(*) using monitors of W emission close to 5nm, containing the quasi-continuum emission W 27+ - W 35+ and spectral lines at 0.794nm emitted by W 46+
Magnetics

For ITER levels of exposure, parasitics are already dominated by sensor effects. Electronics for 12h pulses are demonstrated, but in-vessel sensors, although they could survive, have excessive drift.

**DEMO R&D should concentrate on robust and drift-resistant sensor packages**

Placement of the sensors is extremely important: need locations with good poloidal flux penetration.

For parasitics at the level of the ITER sensors, DEMO will definitely need steady-state measurements to compensate for drifts, ideally in-vessel.

**Most promising technology is metallic Hall probes.**

For shape control, ITER may also well prove plasma position reflectometry is adequate, but this will require dedicated space allocation.

Cabling is as important as the sensors: similar effects and harder to design and maintain.
HALL sensor example

- Success in using Gen 2 DBC technology also for bismuth sensing layers.
- No problem with noise (up to ~150 degC) – noise level about the same as for Cu while, signal is ~2000 times higher.
- Significant loss of sensitivity with rising temperature – quadratic dependence.
Diamond detectors

Candidate detector for ITER n camera:
- Very robust material
- Temperature resistant
- Radiation hard
- Fabrication CVD

Faraday Rotation Measurement Is Promising method in Future Reactor Due to High Resistance to Mirror Degradation

ITER :Measurements of Density ( error 8%) and Temperature( error 30%) possible by polarimetry

Error of $\Delta \theta$: 0.1 degree$^4$
Error of $\Delta \varepsilon$: 0.6 degree$^4$

15 viewing chords, 119 $\mu$m
• In-Line ECE: Integration of ECE system in ECCD Transmission Line. Notch around gyrotron frequency
• Co-located system
• Two implementations
  – TEXTOR (Quasi Optical)
  – AUG (CW, waveguides)
• Good news for DEMO
  – Plasma equilibrium not needed for NTM suppression
BURN CONTROL

\[ P_\alpha \approx C_\alpha \ f_{\text{MIX}} \ (nT)^2 \ V \]
\[ P_{\text{alpha}} = C_\alpha \left\langle ne^2 \right\rangle \ \sigma_v \ E_\alpha \ V \gamma (1-\gamma) \]
\[ \gamma = \frac{n_T}{n_D + n_T} \]
\[ C_\alpha = \text{dilution factor} = (1 - 2f_{He} - Z_{Ar}f_{Ar} - Z_{Be}f_{Be})^2 \ (\text{ITER}) \]
\[ P_{\text{loss}} (\text{W/m}^3) \approx \frac{n_T}{\tau E} \approx n^{1.91} T^{3.26} \]
\[ P_{\text{RAD}} \approx P_{\text{Brem}} \approx Z_{\text{eff}} n^2 T^{1/2} \]
\[ \tau_{\text{EIFB}} y^2 \approx n^{-0.91} T^{-2.26} \]

Close to ignition

\[ \text{for } P_\alpha \approx P_{\text{loss}} \Rightarrow C_\alpha \ (nT)^2 \approx n^{1.91} T^{3.26} \Rightarrow \]
\[ T \approx C_\alpha^{-0.8} n^{-0.07} f_{\text{MIX}}^{0.8} \]
\[ P_{\text{fusion}} \approx 5 \ C_\alpha^{2.6} n^{2.14} f_{\text{MIX}}^{2.6} \]

In general BURN CONTROL is:
- Density Control
- Impurity Control
- Temperature Control
- ISOTOPIC MIX CONTROL

To control the Teq the sensible parameters are:
- \( f_{\text{MIX}} \) and \( C_\alpha \).

To control the burn the sensible parameters are:
- \( ne \), \( f_{\text{MIX}} \) and \( C_\alpha \).

A tolerance of 10% in Pfus implies the possibility of changing
\[ \frac{\delta ne}{ne} \approx 5\% \text{, and } \frac{\delta f_{\text{MIX}}}{f_{\text{MIX}}} \approx 4\% \]
\[ \Rightarrow \text{the accuracy needed for measurement of density is } 1 - 2\% \]
\[ \Rightarrow \text{the accuracy needed for measurement of } f_{\text{MIX}} \text{ is } 1\%. \]
\[ \Rightarrow \text{A tolerance of 10% in the burn temperature implies the capability of changing } f_{\text{MIX}} \text{ and dilution } C_\alpha \text{ by } 12.5\% \]
# Diagnostics for Burn Control

<table>
<thead>
<tr>
<th>Technical Specifications</th>
<th>Diagnostics for</th>
<th>BURN Control</th>
<th>Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>Space Resolution</td>
<td>Time Resolution</td>
</tr>
<tr>
<td>Te (bulk)</td>
<td>5% a/10</td>
<td>&lt;100ms</td>
<td>ECE (Polarimetry)</td>
</tr>
<tr>
<td>Ne</td>
<td>1% a/10</td>
<td>&lt;100ms</td>
<td>Polarimetry, Reflectometry</td>
</tr>
<tr>
<td>Impurities</td>
<td>10% integral</td>
<td>&lt;100ms</td>
<td>VUV-Xray spectr ???</td>
</tr>
<tr>
<td>Zeff(line int.)</td>
<td>&lt;20% integral</td>
<td>&lt;100ms</td>
<td>Vis spectr ???</td>
</tr>
<tr>
<td>Pfus</td>
<td>10% integral</td>
<td>&lt;100ms</td>
<td>Neutronics</td>
</tr>
<tr>
<td>Confined fast ions</td>
<td>20% a/10</td>
<td>100ms</td>
<td>NPA</td>
</tr>
<tr>
<td>nD/nT</td>
<td>10% a/10</td>
<td>&lt;100ms</td>
<td>NPA</td>
</tr>
<tr>
<td>Core He density(nHe/ne)</td>
<td>10% a/10</td>
<td>100ms</td>
<td>??</td>
</tr>
<tr>
<td>Ti(bulk)</td>
<td>10% a/10</td>
<td>100ms</td>
<td>Neutronics</td>
</tr>
</tbody>
</table>

Minimum set of Diagnostics for Burn Control:
- ECE
- Magnetics
- Reflectometry
- Polarimetry
- Neutronics
- VUV spectroscopy
- Vis spectroscopy
- NPA
### Readiness level of neutron diagnostics for DEMO

<table>
<thead>
<tr>
<th>TRL</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL 1</td>
<td>Basic principles observed and reported.</td>
</tr>
<tr>
<td>TRL 2</td>
<td>Technology concept and/or application formulated.</td>
</tr>
<tr>
<td>TRL 3</td>
<td>Analytical and experimental critical function and/or characteristic proof-of-concept.</td>
</tr>
<tr>
<td>TRL 4</td>
<td>Technology basic validation in a laboratory environment.</td>
</tr>
<tr>
<td>TRL 5</td>
<td>Technology basic validation in a relevant environment.</td>
</tr>
<tr>
<td>TRL 6</td>
<td>Technology model or prototype demonstration in a relevant environment.</td>
</tr>
<tr>
<td>TRL 7</td>
<td>Technology prototype demonstration in an operational environment.</td>
</tr>
<tr>
<td>TRL 8</td>
<td>Actual Technology completed and qualified through test and demonstration.</td>
</tr>
<tr>
<td>TRL 9</td>
<td>Actual Technology qualified through successful mission operations.</td>
</tr>
<tr>
<td>System</td>
<td>Likely detector</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Neutron flux monitor system</td>
<td>Fission chambers</td>
</tr>
<tr>
<td>Neutron camera system</td>
<td>Scintillators, TOF</td>
</tr>
</tbody>
</table>
The planning of R&D must take into account that
i) a programme including the selection of tests of minimum set of sensors and control schemes must be carried out on ITER, JT-60SA and other devices available before DEMO comes into operation
ii) the use of codes like TRANSP or/and METIS for DEMO control can be started in the context of ITM (International Tokamak Modelling) activity
1. Burn control: DIAGNOSTICS FOR ALPHA PARTICLES, PLAMA TEMPERATURE, FUEL MIX

2. TRANSPORT CODES AND SYNTHETIC DIAGNOSTICS: An example is METIS CODE

3. Radiation hardening of diagnostics to be used continuously During the Power-plant-like phase
<table>
<thead>
<tr>
<th>R&amp;D NEEDS in DIAG Technology</th>
<th>new concepts of diagnostics TO BE DEVELOPED</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetic sensors</td>
<td>LOST FAST PARTICLES</td>
</tr>
<tr>
<td>mirrors /shutters/cleaning techniques</td>
<td>MAGNETICS</td>
</tr>
<tr>
<td>bolometers</td>
<td>CURRENT PROFILE ( DIFFERENT FROM POLARIMETRY )</td>
</tr>
<tr>
<td>X-ray sensors</td>
<td>SPECTROSCOPY :X-RAY, VIS SPECTROSCPY</td>
</tr>
<tr>
<td>IR cameras</td>
<td>confined fast particles</td>
</tr>
</tbody>
</table>
Tests on JET

1. Diagnostics for fast (alpha) particles

2. Neutron absolute calibration methods

3. Neutron and gamma spectroscopy: new diamond (or SiC) detectors for neutron spectroscopy

4. Low and High energy Neutral Particle Analyzer (JET High-Energy NPA measures the energy distribution function of neutral H, D, T, 3He and 4He in the energy range 0.3 – 4 MeV.)

5. Neutron absorbers for gamma ray spectroscopy

Diamond detector meas and interpretation
Test on TCV

- Fault detection
  - Detect sudden deviation of measurement from model prediction
  - Isolate fault and exclude from reconstruction
The elaboration of DEMO device parameters and concrete implementation is now one of the objectives of fusion community.

The DEMO models are now moving in the direction of a long pulse (3-4 hours) device with main inductive current.

R₀=9m Bₜ=6.5T Iₚ=17MA A=R₀/a=3.6

Diagnostic systems need to be used for the control of burn and machine protection only.

String R&D is starting: key point is resistance of the components to the high Neutron Fluence.

Minimal set of diagnostics for DEMO control includes:
- IR systems (reflectometry, polarimetry)
- Neutronics (neutron/gamma cameras)

R&D needed in Mo and tungsten mirrors
Development of control codes based on physics models.